Rare Dimuon Decays at ATLAS

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for

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Workshop

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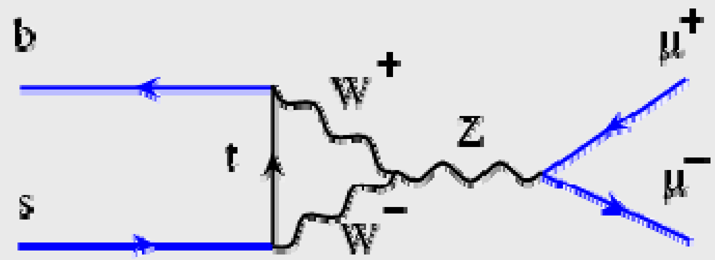
Introduction

Physics: **b → d, s** transitions (**FCNC**) are forbidden at the tree level in SM and occur at the lowest order through one-loop-diagrams **“penguin”** and **“box”**.

Main points for study:

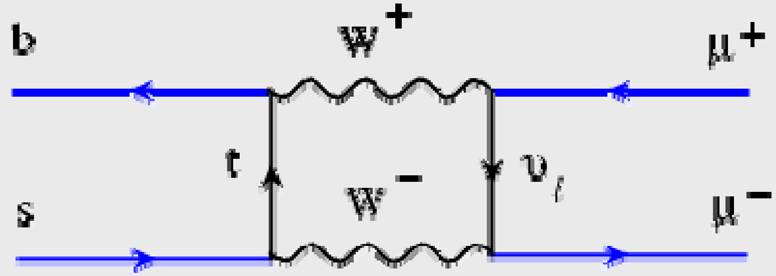


a) **The good test of SM and it’s possible extensions;**

b) **Information of the long-distance QCD effects;**

c) **Determination of the** $|V_{td}|$ **and** $|V_{ts}|$**;**

d) **Some of rare decays can produce the BG to other rare decays (for example:** $B^+ \to \mu^+ \mu^- \ell^+ \nu_\ell$ **as BG to** $B^0_{d,s} \to \mu^+ \mu^-$**).**



Which new rare B-decays measurements can be performed by LHC in comparision with B-factories?

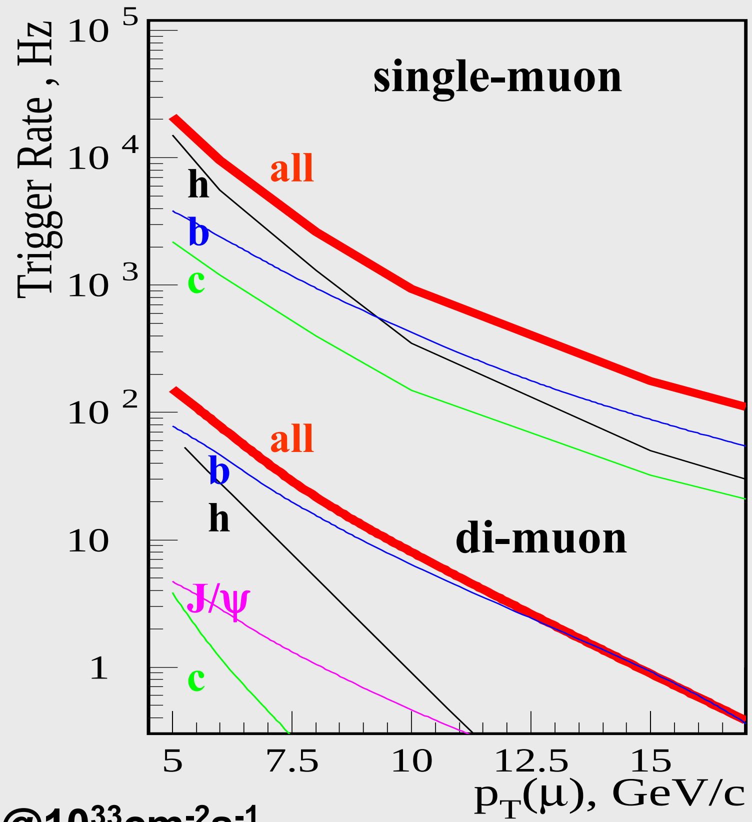
a) The rare decays of B^0_s – meson ($B^0_s \to \varphi\gamma$, $B^0_s \to \varphi\, \mu^+ \mu^-$, and $B^0_s \to \mu^+ \mu^- (\gamma)$) and Λ_b – baryon ($\Lambda_b \to \Lambda\, \mu^+ \mu^-$, $\Lambda_b \to \Lambda\, \gamma$);

b) **Differential distributions** for **rare semileptonic** B-meson decays (dimuon **mass spectra**, forward-backward **asymmetries**) **with sufficient accuracy** for distinguishing **SM and it's extentions**;

c) Branching fractions of **extremely rare decays** $B^0_{d,s} \to \mu^+ \mu^-$ and $B^0_{d,s} \to \mu^+ \mu^- \gamma$ decays have **good sensitivity for some SM extensions**.

ATLAS trigger strategy for di-muonic B-events

ATLAS LVL1, Trigger rates at
initial luminosity (0.5-2.0)×10^{33}cm^{-2}s^{-1}



@10^{33}cm^{-2}s^{-1}

1) The study of two-muons rare decays **$B^0_s \to \mu^+ \mu^-$, $B^0_{d,s} \to (K^*,\varphi)\ \mu^+ \mu^-$** based on LVL1 di-muon trigger (**can be continued at nominal 10^{34} cm^{-2}s^{-1}**).

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2) The study of rare decays:
$B^0_d \to \pi^0\mu^+ \mu^-$ and **$B^0_s \to \mu^+ \mu^- \gamma$** based on LVL1 di-muon trigger and single muon LVL1 (μ6) with photons reconstruction in EM CALO.

$B^0_{d,s} \to \mu^+ \mu^-$ decays at ATLAS

$Br_{SM} \sim 10^{-9} – 10^{-10}$

All experimental limits are <u>100 times higher</u>, than SM theoretical predictions.

Motivation for $B^0_{d,s} \rightarrow \mu^+ \mu^-$ study

th) **Clear theoretical picture** **for SM and it's extensions for branching ratio predictions.**

th') **Good** **potential sensitivity for the SUSY (for example: in MSSM** $Br \sim \tan^6\beta / M^2_H$ **).**

ex) **Only LHC** **<u>can measure</u>** **branching ratios of the rare muonic decays in SM.**

ex') **ATLAS** **(and CMS) will have some** **advantages over LHCb** **studying rare muonic channels** **at nominal** **(10^{34})** **luminosity.**

ex'') **Simple signature** **for experimental search.**

$B^0_{d,s} \to \mu^+\mu^-$ simulation at ATLAS

1) 1998-1999-years simulation TDR ATLAS Detector layout

Full detector simulation and reconstruction for initial and nominal LHC luminosity,
signal + combinatorical background

After 3 year LHC at $L=10^{33}$ $cm^{-2}s^{-1}$ ($30\ fb^{-1}$)

B^0_d : 4 signal ev., B^0_s : 27 signal ev., 93 BG ev. common to both

After 1 year LHC at $L=10^{34}$ $cm^{-2}s^{-1}$ ($100\ fb^{-1}$)

B^0_d : 14 signal ev., B^0_s : 92 signal ev., 660 BG ev. common to both

$B^0_d \to \mu^+\mu^-$: $3*10^{-10}$ upper limit at CL 95%

$B^0_s \to \mu^+\mu^-$: 2.8σ at 3year@10^{33} and combining with 1year@10^{34} - 4.3σ

CERN/LHCC/99-15, ATLAS TDR 15, 25 MAY 1999;
"1999 Workshop on SM Physics (and more) at the LHC", CERN Yellow Report, **CERN-2000-004**.

2) 2002-2005 simulations with Final ATLAS Detector layout and with new software

DC1: ATLAS B-Physics Group, **ATL-PHYS-2005-002**

DC2+ Rome Production: ATLAS Physics workshop (Rome),
http://agenda.cern.ch/fullAgenda.php?ida=a044738

ATLAS sensitivity on $Br(B^0_s \to \mu^+\mu^-)$ with Final detector layout

Integral LHC Luminosity	BG ev. $p_T(\mu) > 6$ GeV, $\Delta R_{\mu\mu} < 0.9$	SES	Expected Signal ev. after cuts	Expected BG ev. after cuts	ATLAS upper limit at 90% CL	CDF&D0 best upper limit at 90% CL
100 pb^{-1}	**6.0×10^4**	**2.7×10^{-8}**	**~ 0**	**~ 0.2**	**6.4×10^{-8}**	**1.2×10^{-7}**
10 fb^{-1}	**6.0×10^6**	**2.7×10^{-10}**	**~ 7**	**~ 20**	**7.0×10^{-9}**	
30 fb^{-1}	**1.8×10^7**	**0.9×10^{-10}**	**~ 21**	**~ 60**	**6.6×10^{-9}**	

1) We get the cross section of B^0_s multiplied by acceptance of $B^0_s \to \mu^+\mu^-$ decay with $p_T(\mu)>6$ GeV and $|\eta(\mu)|<2.5$ from Rome PYTHIA samples : **$\sigma(B_s)*\alpha = 0.42$ μb;**

2) We get the background ($b\bar{b} \to \mu\mu X$) cross section **σ(BG)** with $pT(\mu) > 6$ GeV and $|\eta(\mu)| < 2.5$ from Rome PYTHIA samples: **σ(BG) = 600 pb**;

3) SES - Single event sensitivity for $B^0_s \to \mu^+\mu^-$

SES = [(1 $B_s \to \mu6\mu6$ event)/(total number of BG events)]×[σ(BG)/ ($\sigma(B_s)*\alpha$) * ε_μ^2];

4) For ATLAS upper limit calculation we have used CDF code http://www-cdf.fnal.gov/physics/statistics/statistics_software.html.

BG for $B^0_{d,s} \to \mu^+\mu^-$ decays

In order to find physics beyond SM in rare muonic decays, we need to know <u>all possible SM BG</u>.

1. In ATLAS conditions the largest BG is coming from $b\bar{b}\,(b\bar{b}b\bar{b},\, b\bar{b}c\bar{c}) \to \mu\mu X$ processes, with muons originating mainly from semileptonic b(c) decays.

2. Other <u>important BG</u> can be produced by <u>decays with small branching ratios</u> (rare decays!) or <u>exotic decays</u>, which are NOT included in standard MC-generators (PYTHIA, for example). These processes may be potentially dangerous as they <u>have signatures very similar</u> to $B \to \mu\mu$ signal in area of their phase space.

$B^{0\pm} \to \pi^{0\pm}\mu^+\mu^-$ as BG for $B^0_{d,s} \to \mu^+\mu^-$

1. The branching ratios of $B^{0\pm} \to \pi^{0\pm}\mu^+\mu^-$ decays approximatly equal to 10^{-8} and are larger than branching ratios of rare leptonic decays $B^0_{d,s} \to \mu^+\mu^-$.

2. The background would come from **soft pions** escaping the identification and leaving the invariant dimuon mass

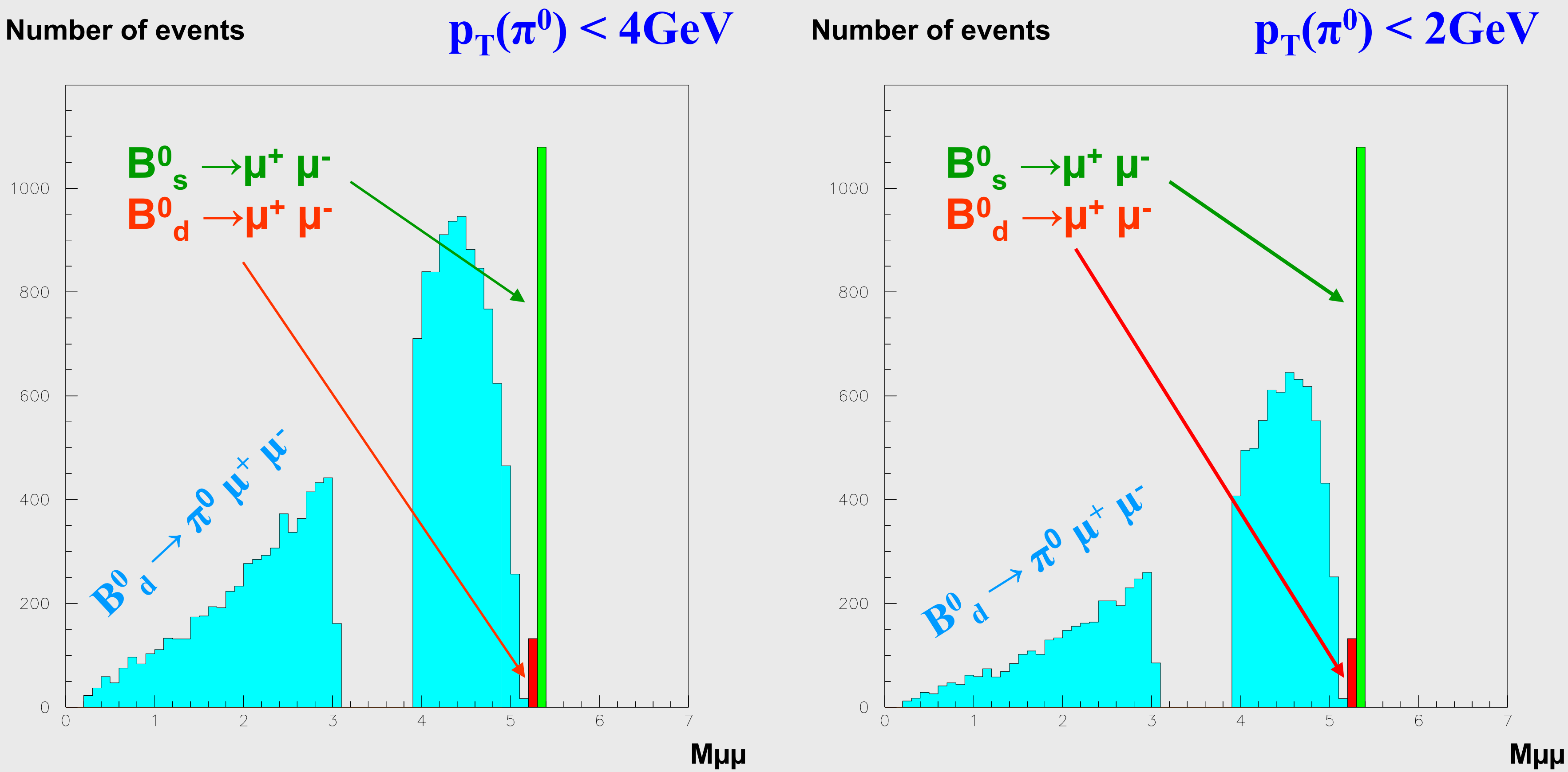
$$M_{\mu\mu} = M_B - M_\pi.$$

within the **limits of B→μμ mass resolution** (**σ ~ 80 MeV**).

3. Detailed detector simulation will allow to determine strategies to further reduce the contributions of these decays.

4. At first step (particle level study) there were revealed basic problems of $B^{0\pm} \to \pi^{0\pm}\mu^+\mu^-$ as a background to $B^0_{d,s} \to \mu^+\mu^-$ (see next slides).

$B^0_d \to \pi^0 \mu^+ \mu^-$ as BG for $B^0_{d,s} \to \mu^+ \mu^-$



$|\eta(\mu)| < 2.5$, $p_T(\mu) > 6$ GeV, $\pi^0 \to \gamma\gamma$.

The particle level simulation of $B^0_d \to \pi^0 \mu^+ \mu^-$ for SM

(<u>no cuts selecting μμ-pairs pointing to primary vertex applied</u>).

$B^+ \rightarrow \mu^+\mu^- \ell^+\nu_\ell$ and $B_c \rightarrow \mu^+\mu^- \ell^+\nu_\ell$ as BG for $B^0_{d,s} \rightarrow \mu^+\mu^-$

Roughly: the branching ratio of $B^+ \rightarrow \mu^+\mu^- \ell^+\nu_\ell$ is

$$Br(B^+ \rightarrow \mu^+\mu^- \ell^+\nu_\ell) \approx 5*10^{-6},$$

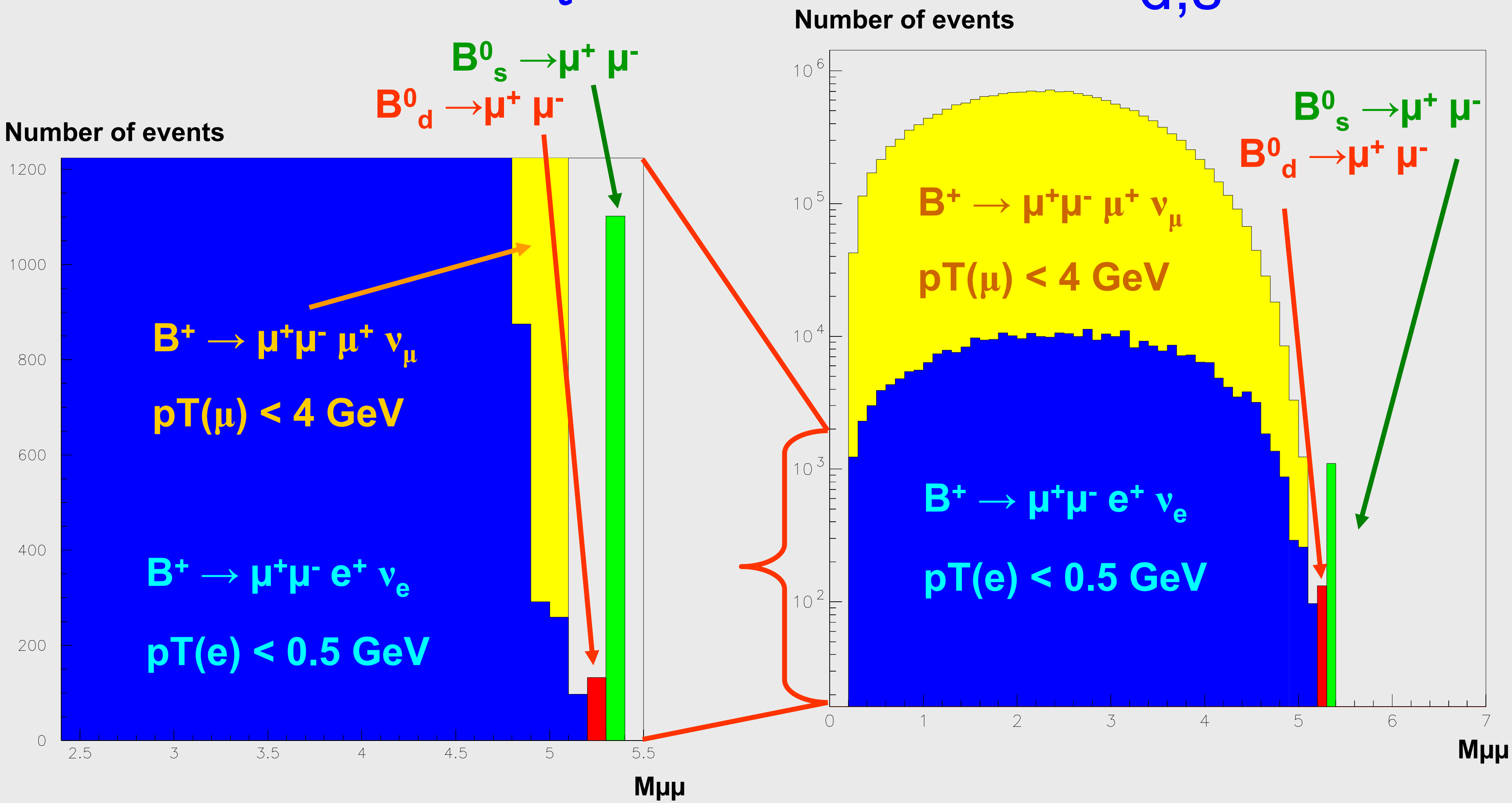
the branching ratio of $B_c \rightarrow \mu^+\mu^- \ell^+\nu_\ell$ is

$$Br(B_c \rightarrow \mu^+\mu^- \ell^+\nu_\ell) \approx 8*10^{-5}.$$

Because of the fact, that B_c – meson's cross section is 400 times smaller than cross section of B^+ at LHC energy, this decay channels gives approximately equal BG for $B^0_{d,s} \rightarrow \mu^+\mu^-$.

This BG seems to be very significant comparing with BG from $B^{0\,\pm} \rightarrow \pi^{0\,\pm}\mu^+\mu^-$ decays (see particle level example for decays $B^+ \rightarrow \mu^+\mu^- \ell^+\nu_\ell$ on the next slide).

$B^+ \rightarrow \mu^+\mu^- \ell^+\nu_\ell$ as BG for $B^0_{d,s} \rightarrow \mu^+\mu^-$



For muons in $M_{\mu\mu}$: $|\eta(\mu)| < 2.5$, $p_T(\mu) > 5$ (or 6) GeV.

The particle level phase space simulation of $B^0_d \rightarrow \mu^+\mu^- \ell^+\nu_\ell$

(no cuts selecting μμ-pairs pointing to primary vertex applied yet!).

Rare semileptonic b-decays at ATLAS

$Br_{SM} \sim 10^{-6} - 10^{-7}$

Motivation for study of $B^0_{d(s)} \to K^*(\varphi)\mu^+\mu^-$

th) **Good agreement between different nonperturbative theoretical models;**

th') **Branching ratios and differential distributions (dimuon-mass spectra, A_{FB}) are sensitive to the SM extentions;**

ex) **It is possible to study the rare semileptonic decays at initial LHC luminosity;**

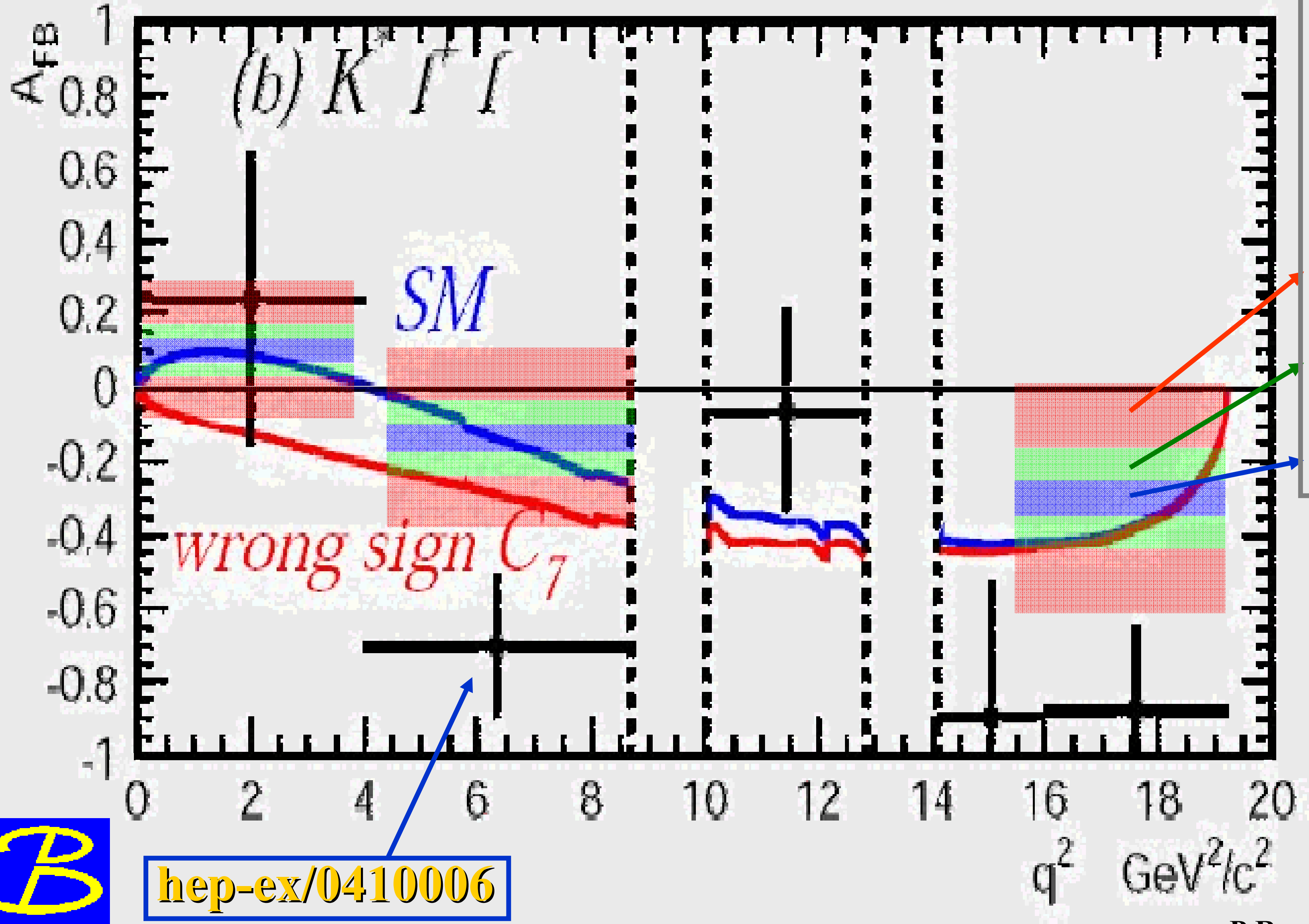
ex') **ATLAS will have enough statistics at initial luminosity for precise measurement of differential distributions.**

Expected ATLAS statistics at 30 fb^{-1}

Decay Cannels	Reconstructed Signal events	BG after all cuts
$B^0_d \rightarrow K^* \mu^+ \mu^-$	3000	< 3000
$B^0_s \rightarrow \varphi \mu^+ \mu^-$	900	< 3000
$\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$	1500	in progress

Full detector simulation and reconstruction for <u>final ATLAS Detector layout with new software</u> at initial LHC luminosity: signal and <u>combinatorical background</u> (in progress). Trigger efficiencies included.

A_{FB} for $B^0_d \to K^*(892)\mu^+\mu^-$ decay



hep-ex/0410006

P.Reznichek

CONCLUSION

1. Already during the first year of LHC, with luminosity just **100 pb^{-1}** ATLAS **can exceed best CDF and D0 current** upper limit on branching ratios of **$B^0_s \to \mu^+\mu^-$** decay.
2. After **30 fb^{-1}** (equivalent to 3 years at initial luminosity) ATLAS **will be able to achieve sensitivity at level of SM predictions for $B^0_s \to \mu^+\mu^-$**.
3. Under the same conditions ATLAS will **have enough statistics** for **precise measurement** of **differential distributions** of rare semileptonic decays.
4. Program of ATLAS rare muonic decays measurements **can be continued** at **nominal** LHC **luminosity 10^{34} cm^{-2} s^{-1}!**

Appendix

The basic theoretical description -I

Effective Hamiltonian for b → d,s transition:

$$H_{eff}(b \to q) \sim G_F V^*_{tq} V_{tb} \sum C_i(\mu)\, O_i(\mu),$$

includes the lowest EW-contributions and perturbative QCD corrections for Wilson coefficients $C_i(\mu)$.

μ - scale parameter ~ **5 GeV** : separates **SD** (perturbative) and **LD** (nonperturbative) contributions of the strong interactions.

SM NLO: A.Buras, M.Munz, *PRD52, p.182, 1995*

SM NNLO: C.Bobeth et al., *JHEP 0404, 071, 2004*

MSSM NNLO: C.Bobeth et al., *NPB713, p522, 2005*

The basic theoretical description -II

$O_i(\mu)$ – set of the basic operators **(specific for each model: SM, MSSM, LR and others);**

LD (nonperturbative) contribution of the strong interactions are contained in the hadronic matrix elements:

$$\langle \text{final hadronic states} \,|\, O_i\ (\mu) \,|\, \text{initial hadronic states} \rangle$$

and are described in the terms of relativistic invariant function - **transition formfactors**.

Need the nonperturbative methods (SR, QM, Lat).

SM Theoretical Branching Ratios Predictions

$B^0_s \to \mu^+ \mu^-$	$Br(B^0_s \to \mu^+ \mu^-) = 3.5 * 10^{-9}$ at $\lvert V^*_{ts} V_{tb} \rvert^2 = 2.2 * 10^{-3}$
$B^0_d \to \mu^+ \mu^-$	$Br(B^0_d \to \mu^+ \mu^-) = 0.9 * 10^{-10}$ at $\lvert V^*_{td} V_{tb} \rvert^2 = 6.9 * 10^{-5}$
$B^0_d \to K^* \mu^+ \mu^-$ $B^0_s \to \varphi \mu^+ \mu^-$ $B^0_d \to \pi^0 \mu^+ \mu^-$ $B^\pm_d \to \pi^\pm \mu^+ \mu^-$	$Br(B^0_d \to K^* \mu^+ \mu^-) = 1.3 * 10^{-6}$ from PDG'04 $Br(B^0_s \to \varphi \mu^+ \mu^-) / Br(B^0_d \to K^* \mu^+ \mu^-) = 0.8$ D.Melikhov, N.Nikitin, S.Simula, PRD57, 6814, 1998 D.Melikhov, B.Stech, PRD62, 014006, 2000 A.Buras, M.Munz, PRD52, 186, 1995 $Br(B^0_d \to \pi^0 \mu^+ \mu^-) = 2.0 * 10^{-8}$ at $\lvert V^*_{td} V_{tb} \rvert^2 = 6.9 * 10^{-5}$ $Br(B^\pm_d \to \pi^\pm \mu^+ \mu^-) = Br(B^0_d \to \pi^0 \mu^+ \mu^-)$
$B^0_s \to \mu^+ \mu^- \gamma$	$Br(B^0_s \to \mu^+ \mu^- \gamma) = 1.9 * 10^{-8}$ at $\lvert V^*_{ts} V_{tb} \rvert^2 = 2.2 * 10^{-3}$ D.Melikhov, N.Nikitin, PRD70, 114028, 2004 F.Kruger, D.Melikhov, PRD67,034002, 2003 A.Buras, M.Munz, PRD52, 186, 1995
$\Lambda_b \to \Lambda \mu^+ \mu^-$	$Br(\Lambda_b \to \Lambda \mu^+ \mu^-) = 2.0 * 10^{-6}$ C-H.Chen, C.Q.Geng, PRD64, 074001, 2001 T.M.Aliev et.al. , NPB649, p. 168-188 , 2003

A4

"Rome production": 2005 – Data Samples

Generation (with theoretical matrix elements), full simulation, digitization and reconstruction with **9.0.4** and **10.0.1** software releases, analysis of AOD in **10.0.1** .

Signal channels:

$B \rightarrow \mu6\mu6$ Rome production. **5 kEv** in analysis (AOD)

$B \rightarrow K^{*0}\mu6\mu4$ Private (evgen-simul-digi-reco) **30 kEv** (AOD)

$B \rightarrow \varphi\ \mu6\mu4$ Private (evgen-simul-digi-reco) **12 kEv** (AOD)

$\Lambda_b \rightarrow \Lambda\ \mu5\mu5$ Private (evgen-simul-digi-reco) **~50 kEv** (AOD)

Background samples:

$bb \rightarrow \mu6\mu6X$ **~50kEV** included cut on $M(\mu\mu) \sim M(B^0_s)$

$bb \rightarrow \mu4\mu4X$ **~23kEV** for B-decays and **~31kEv** for Λ_b-decays

Upper limits for rare muonic decays

CDF Run 2: **$Br(B_s \rightarrow \mu\mu) < 2.0 \times 10^{-7}$ @ 95% CL**
(hep-ex/0508036)

D0 Run 2: $Br(B_s \rightarrow \mu\mu) < 3.7 \times 10^{-7}$ @ 95% CL
(D0-Note 4733-Conf, Preliminary)

D0 Run 2: $Br(B_s \rightarrow \mu\mu) < 5.0 \times 10^{-7}$ @ 95% CL
(Phys. Rev. Letters 94, 071802 (2005))

CDF Run 2: $Br(B_s \rightarrow \mu\mu) < 7.5 \times 10^{-7}$ @ 95% CL
(Phys. Rev. Letters 93, 032001 2004)

CDF Run 2: **$Br(B_d \rightarrow \mu\mu) < 3.9 \times 10^{-8}$ @ 90% CL**
(hep-ex/0508036)

BaBar: $Br(B_d \rightarrow \mu\mu) < 8.3 \times 10^{-8}$ @ 90% CL
(hep-ex/0408096)

CDF Run 2: $Br(B_d \rightarrow \mu\mu) < 1.5 \times 10^{-7}$ @ 90% CL
(Phys. Rev. Letters 93, 032001 2004)

Belle: $Br(B_d \rightarrow \mu\mu) < 1.6 \times 10^{-7}$ @ 90% CL
(Phys. Rev. D 68, 111101 (R) (2003))

All experimental limits are 100 times higher, than SM theoretical predictions.

$B^0_s \to \mu^+\mu^-$ decays in ATLAS: Rome production at 2005 year

Signal, BG and efficiencies of selection cuts (10 fb^{-1})

Cuts	BG: $b\bar{b} \to \mu\mu X$		B^0_s - Signal	
Vertexing procedure	CTMVFT	**VKalVrt**	CTMVFT	**VKalVrt**
$p_T(\mu) > 6$ Gev, $\Delta R_{\mu\mu} < 0.9$	**6.0×10^6 events**		**50 events**	
$M(\mu\mu)=M_B{}^{+140}{}_{-70}$ MeV	2×10^{-2}	—	0.77	—
Isolation cut: no ch.tracks p_T>0.8 GeV in cone with $\theta < 15^o$	5×10^{-2}	**5×10^{-2}**	0.36	**0.36**
$\sigma < 90\mu m$, $L_{xy}/\sigma > 15$, $\alpha < 1^o$	2.8×10^{-3}		0.2	
$L_{xy}/\sigma > 11$, $\chi^2 < 15$		**$< 0.7\times10^{-4}$**		**0.4**
Number of events after cuts	15±10	**20±20**	3	**7**

B-meson hadronic decays as BG for $B^0_{d,s} \to \mu^+\mu^-$

Another important BG for $\mathbf{B^0_{d,s} \to \mu^+\mu^-}$ is **two-body hadronic decays** of B-mesons, when one (or both) final hadrons have short lifetime, and decayed inside ATLAS Inner Detector with high probability.

For example:

$$\mathbf{Br(B^0_d \to (D^+ \to \mu^+ X_s)(D^- \to \mu^- X_s)\ in\ ID) \approx 10^{-6}},$$

$$\mathbf{Br(B^0_d \to (D^+ \to \mu^+ X_d)(D^- \to \mu^- X_d)\ in\ ID) \approx 10^{-8}}.$$

This decay and similar decays $\mathbf{B^0_d \to K^+ D^-}$, $\mathbf{B^0_s \to K^+ D^-_s}$ and $\mathbf{B^0_s \to D^{*+}_s D^{*-}_s}$ are **not included in PYTHIA 6.x!**

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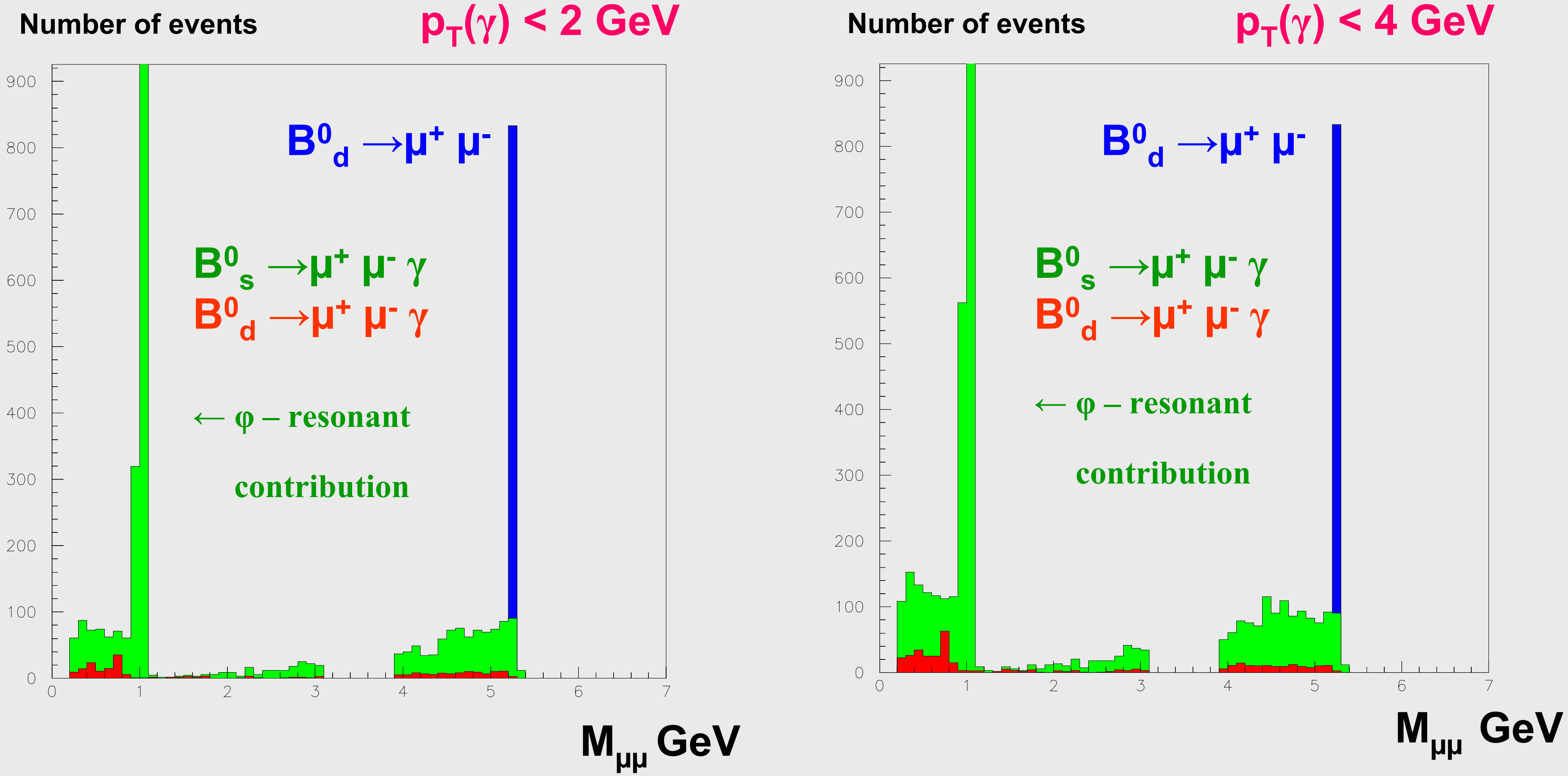
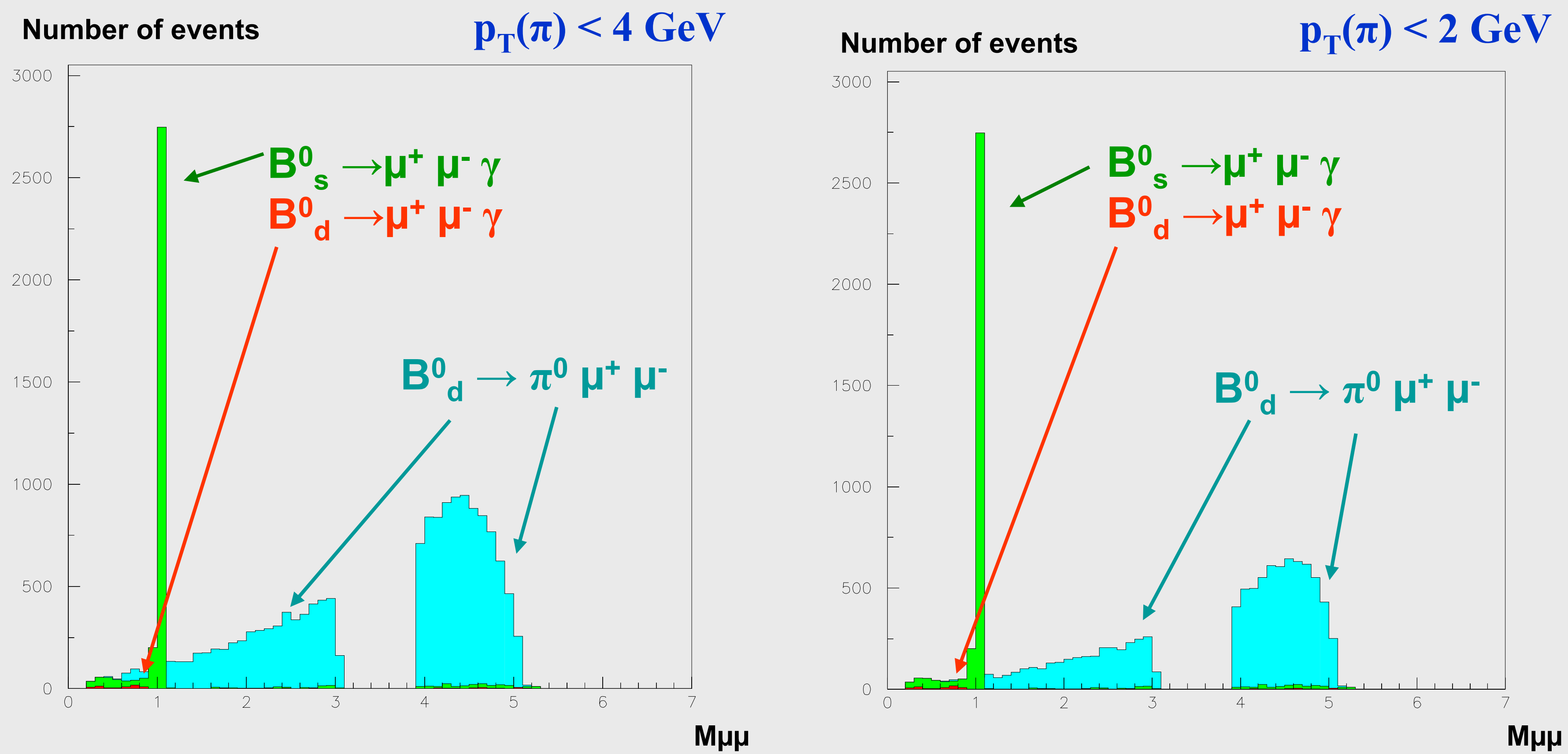
$B^0_{d,s} \to \mu^+\mu^-\gamma$ as BG to $B^0_d \to \mu^+\mu^-$



$|\eta(\mu)| < 2.5$, $p_T(\mu) > 6$ GeV

The decays $B^0_{d,s} \to \mu^+ \mu^- \gamma$ are not essential background for the decay $B^0_d \to \mu^+ \mu^-$.

$B^0_d \to \pi^0 \mu^+ \mu^-$ as BG to $B^0_{d,s} \to \mu^+\mu^-\gamma$



$|\eta(\mu)| < 2.5$, $p_T(\mu) > 6$ GeV, $\pi^0 \to \gamma\, \gamma$.

The particle level simulation $B^0_d \to \pi^0 \mu^+ \mu^-$ for SM

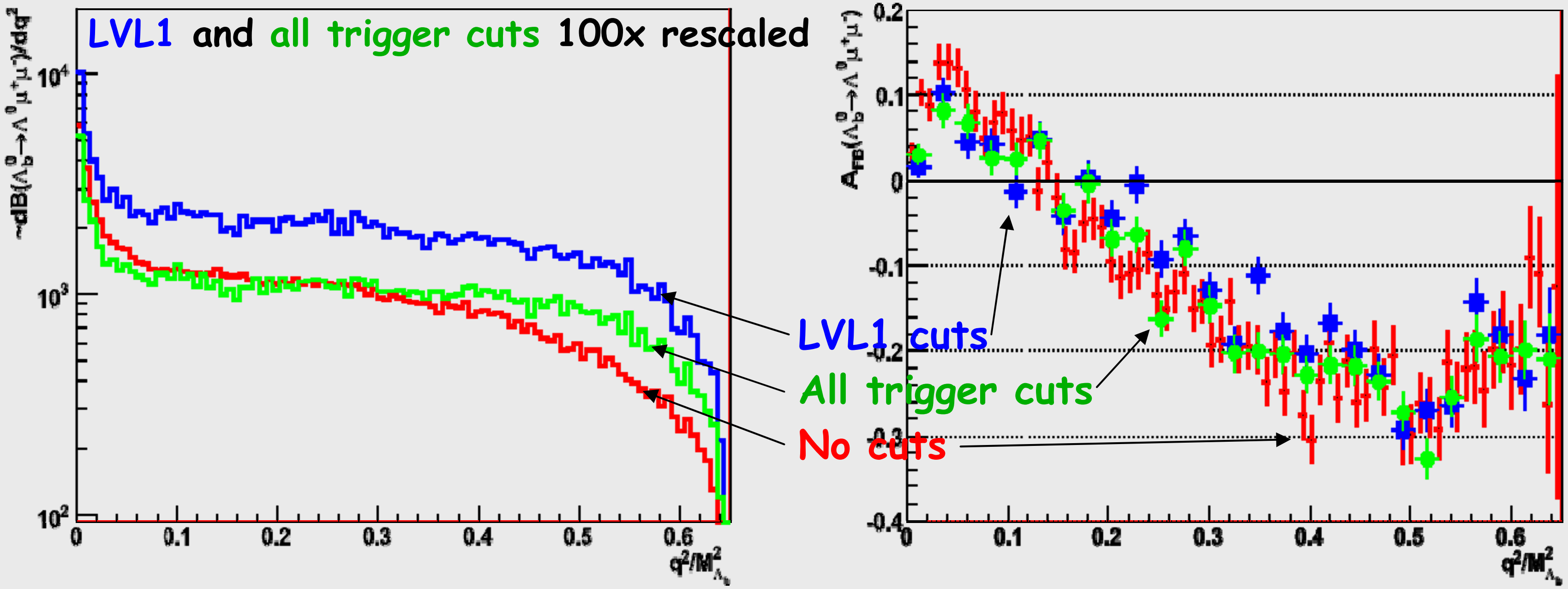
(no cuts selecting μμ-pairs pointing to primary vertex applied yet!).

Impact of Trigger Cuts for $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$

- expected number of triggered events for 30 fb^{-1}

Λ_b - production	σ_{bb} = 500μb, Br($b \rightarrow \Lambda_b$) = 0.071	1.1×10^{12}
Λ_b rare decay	Br($\Lambda_b \rightarrow \Lambda\mu\mu$) = 2×10^{-6}, Br($\Lambda \rightarrow p\pi$) = 0.64	1.400.000
Di-muon LVL1 cuts	p_T > 6/4 GeV, $\lvert\eta\rvert$ < 2.5	26.000
Hadron cuts	p_T >0.5 GeV, $\lvert\eta\rvert$ < 2.5	14.000

- trigger cuts prefers higher di-muon invariant masses and slightly lowers absolute value of A_{FB} in region of lower di-muon masses



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